MAX-PLANCK-INSTITUT FÜR STRÖMUNGSFORSCHUNG

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International Union of Theoretical and Applied Mechanics

Symposium

on

ADIABATIC WAVES IN LIQUID-VAPOR SYSTEMS

Göttingen: 28. August - 1. September 1989

Chairmen: Gerd E.A. Meier & Philip A. Thompson
Secretary: Tomasz A. Kowalewski

ABSTRACTS
OF THE CONTRIBUTED PAPERS

August 1989

GÖTTINGEN

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Preface

It is a great pleasure to welcome you on behalf of the Organizing Committee to the IUTAM Symposium on Adiabatic Waves in Liquid Vapor Systems. We are impressed by the quality of the abstracts which have been submitted and the rich diversity of the topics which have been addressed. At last count, we have participants from more than fourteen nations - the gathering is thus truly international and justifies the name of the sponsoring organization: International Union of Theoretical and Applied Mechanics.

The general objective of the Symposium is to bring together specialists in the field of rapid phase changes, for the presentation of new results and the discussion of outstanding problems and goals. Emphasis is on physical results, new phenomena and predictive theoretical models. The overall Symposium topic is fast adiabatic phase changes in liquid-vapor systems and related phenomena.

In recent years, a variety of rapid phase-change phenomena, often with surprising properties, have been discovered. These phase changes are typically driven by pressure changes, rather than heat transfer (an exception is to vapor explosion, sometimes called explosive boiling). At the same time, new developments have modified our understanding of old fields such as cavitation and boiling. We are dealing with the developments of the last 15 years, originating from many different countries, which have not yet been the subject of an international meeting. The interest is in both the physical phenomena themselves and their applications.

This volume contains, in alphabetic order, the abstracts of papers accepted for presentation. As care has been taken to invite the competent active workers in the field, we hope those papers contain the latest development in research on the adiabatic waves in two-phase systems.

August 1989

Gerd E.A. Meier

Philip Thompson

Contents

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Sponsoring Organizations and Companies

The Organizing Committee wishes to acknowledge financial support of the conference kindly provided by:

- International Union of Theoretical and Applied Mechanics.
- U.S. Army Research, Development & Standarization Group (UK), London
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- Deutsche Babcock Werke Aktiengesellschaft in Oberhausen
- Krupp Atlas Elektronik GmbH in Bremen
- Kreissparkasse Göttingen.

General Information

All lectures will be held in the lecture hall of the Max-Planck-Institut für Strömungsforschung, Building 8, Bunsenstraße 10.

Coffee breaks will take place in the lobby of the lecture hall.

Cafeteria lunch will be available in a canteen of the institute.

The Symposium Office will be open during scientific sessions in the lobby of the lecture hall for general inquiries and assistance in all problems, that may arise. Local participants, wearing pink badges, will also be ready to help you.

The telephone number of the Symposium Office will be 0551/709-2777 (for local calls: 709-2777).

A discussion room will be provided in Building 2, fourth floor (opposite Build-ing 8). Personal assistance (and tea) will be available there.

Preliminary Program

1. Liquefaction shock waves and evaporation waves.

Monday a.m., Aug. 28th, 1989

"EVAPORATION WAVE MODEL FOR SUPERHEATED LIQUIDS"
J.E. Shepherd (Troy).

"EVAPORATION WAVES IN LIQUIDS OF HIGH MOLAR SPECIFIC HEAT"
H. Chaves, T. Kurschat, G.E.A. Meier (Göttingen).

"AN EXPERIMENTAL STUDY OF EVAPORATION WAVES IN A SUPERHEATED LIQUID"
L. Hill, B. Sturtevant (Pasadena).

"WAVES IN REACTIVE BUBBLY LIQUIDS"
A.E. Beylich, A. Gülhan (Aachen).

Monday p.m., Aug. 28th, 1989

"DETERMINATION OF CONDENSATION PARAMETER OF VAPORS BY USING A SHOCK-TUBE"
S. Fujikawa, M. Maerefat (Kyoto).

"VAPOR CONDENSATION BEHIND A SHOCK WAVE PROPAGATING THROUGH VAPOR-LIQUID TWO-PHASE MEDIA"
Y. Kobayashi (Tsukuba).

"A QUALITATIVE THEORY OF LIQUEFACTION SHOCKS"
V. Roytburd (Princeton).

"AN INVISCID APPROACH TO PHASE TRANSITION PROBLEM"
H. Hattori (Morgantown).

"INTERACTION OF UNDERWATER SHOCK WAVES WITH AIR BUBBLES"
K. Takayama, A. Abe (Sendai).

2. Condensation in flow, boiling.

Tuesday a.m., Aug. 29th, 1989

"PHASE CHANGES OF A LARGE-HEAT-CAPACITY FLUID IN TRANSCRITICAL EXPANSION FLOWS"
E. Zauner, G.E.A. Meier (Göttingen).

"EXPERIMENTAL INVESTIGATION AND COMPUTER ANALYSIS OF SPONTANEOUS CONDENSATION IN STATIONARY NOZZLE FLOW OF CO_2/AIR MIXTURES"
K. Bier, F. Ehrler, M. Niekrawietz (Karlsruhe).

"SPONTANEOUS CONDENSATION IN STATIONARY NOZZLE FLOW OF CARBON DIOXIDE IN A WIDE RANGE OF DENSITY"
K. Bier, F. Ehrler, G. Theis (Karlsruhe).

"AN ASYMPTOTIC PREDICTIVE METHOD FOR GAS DYNAMICS WITH NON-EQUILIBRIUM CONDENSATION"
C.F. Delale (Istanbul).

"STATIONARY AND MOVING NORMAL SHOCK WAVES IN WET STEAM"
A. Guha, J.B. Young (Cambridge).

"A NUMERICAL STUDY OF NITROGEN CONDENSATION IN 2-D TRANSONIC FLOW IN CRYOGENIC WIND TUNNELS"
G. Schnerr, U. Dohrmann (Karlsruhe).

Tuesday p.m., Aug. 29th, 1989

"EXPLOSIVE BOILING. SOME EXPERIMENTAL SITUATIONS"
V.P.Skripov, O.A. Isaev (Sverdlovsk).

"THE DEVELOPMENT OF CAVITY CLUSTERS IN TENSILE STRESS FIELDS"
K.A. MØrch (Lyngby).

"VAPOR-LIQUID PHASE CHANGE STUDIED BY MEANS OF A SHOCK TUBE EXPANSION-COMPRESSION PROCESS"
F. Peters (Essen).

"A SIMPLE DISCRETE KINETIC MODES RESEMBLING RETROGRADE GASES"
K. Piechór (Warszawa).

"ON THE SIMILARITY CHARACTER OF AN UNSTEADY RAREFACTION WAVE IN A GAS-VAPOUR MIXTURE WITH CONDENSATION"
H.J. Smolders, M.E.H. van Dongen (Eindhoven).

"FIRST RESULTS FOR UNSTEADY FLOW WITH END STATES NEAR THE LIQUID-VAPOR CRITICAL POINT"
P.A. Thompson, J.E. Shepherd, H.J. Cho, S.Can Gulen (Troy).

3. Non-equilibrium in dynamic systems, critical phenomena.

Wednesday a.m., Aug. 30th, 1989

"INVESTIGATION OF NONEQUILIBRIUM GRAVITATIONAL EFFECT NEAR THE CRITICAL POINT BY INTERNAL GRAVITATIONAL WAVES"
A.A. Borisov, Al.A. Borisov, V.E. Nakoryakov (Novosibirsk).

"EFFECT OF THERMODYNAMIC DISEQUILIBRIUM ON CRITICAL LIQUID-VAPOR FLOW CONDITIONS"
Z. Bilicki, J. Kestin (Gdansk/Providence).

"WAVE PROPAGATION IN FLOWING BUBBLY LIQUID"
S. Morioka (Kyoto).

"STABILITY OF SHOCK WAVES AND GENERAL EQUATIONS OF STATE"
V.M. Teshukov (Novosibirsk).

"LIQUEFACTION SHOCKS AND RAREFACTION WAVES IN RETROGRADE AND REGULAR FLUIDS WITH DOWNSTREAM STATES NEAR THE LIQUID-VAPOR THERMODYNAMIC CRITICAL POINT"
S.C.Gulen (Troy).

4. Cavitation waves and evaporation waves.

Thursday a.m., Aug. 31th, 1989

"STRONG EVAPORATION FROM A PLANE CONDENSED PHASE"
Y. Sone, H. Sugimoto (Kyoto).

"FILM BOILING PHENOMENA IN LIQUID-VAPOR INTERFACES"
H. Gouin (Marseille).

"ON THE MACROSCOPIC BOUNDARY CONDITIONS AT THE INTERFACE FOR A VAPOUR-GAS MIXTURE"
Y. Onishi (Tottori).

"KORTEWEG THEORY AND VAN DER WAALS FLUIDS"
M. Slemrod (Madison).

5. Acoustic phenomena in two-phase systems, cavitation.

Thursday p.m., Aug. 31th, 1989

"CAVITATION BEHIND TENSION WAVES"
J. Bode, G.E.A. Meier, M. Rein (Göttingen).

"ACOUSTICS OF TRAVELLING BUBBLE CAVITATION"
J. Buist (Twente).

"MODELLING OF FINITE LIQUID VOLUMES UNDER SHOCK LOADING"
N.N. Chernobayev (Novosibirsk).

"EFFECT OF ULTRASOUND POWER ON SPECTRAL DISTRIBUTION AND SONOLUMINESCENCE INTENSITY OF WATER"
Y.T. Didenko, T.V. Gordeychuk, V.L. Koretz (Vladivostok).

"LIQUID-VAPOR PHASE CHANGE AND SOUND ATTENUATION"
H. Lang (Göttingen).

"NONSTATIONARY WAVE PROCESSES IN BOILING MEDIA"
V.E. Nakoryakov, B.G. Pokusaev, N.A. Pribaturin, S.I. Lezhnin, E.S. Vasserman (Novosibirsk).

"UNIVERSAL BUBBLE SIZE DISTRIBUTION IN INSONIFIED LIQUIDS"
A.O. Maksimov (Vladivostok).

6. Vapor explosions.

Friday a.m., Sept. 1st, 1989

"HYDRODYNAMICS OF EXPLOSION: EXPERIMENT AND MODELS"
V.K. Kedrinskii (Novosibirsk).

"VAPOR DETONATIONS IN SUPERHEATED FLUIDS"
G.R. Fowles (Washington).

"PROPERTIES OF KINEMATIC WAVES IN TWO-PHASE PIPE FLOWS"
J.A. Bouré (Grenoble).

"PROPAGATION OF A VAPOR EXPLOSION IN A CONFINED GEOMETRY"
D.L Frost, G., Ciccarelli, C. Zarafonitis (Montreal).

7. Multiphase flow, shock propagation.

Friday p.m., Sept. 1st, 1989

"GENERALIZED DIFFUSION THEORY OF BUBBLY AIR-WATER TWO-PHASE FLOW"
Nguyen Van Diep (Hanoi).

"EQUATIONS FOR ONE-DIMENSIONAL UNSTEADY FLOW OF BUBBLY LIQUIDS"
A.P. Szumowski (Warsaw).

"SHOCK WAVE PROPAGATION IN LOW TEMPERATURE FLUIDS AND PHASE CHANGE PHENOMENA"
K. Maeno (Muroran).

WAVES IN REACTIVE BUBBLY LIQUIDS

Alfred E. Beylich and Ali Gülhan

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ABSTRACT

When shock waves of a certain strength are introduced into a two-phase system consisting of a liquid (glycerine) as matrix and dispersely distributed bubbles containing a premixed reactive gas mixture (H_2+O_2+Ar), a stable precursor wave with constant speed and amplitude is initiated. Detailed studies of the dynamics and thermodynamics of single bubbles, exposed to a shock wave, show that, due to adiabatic change in the bubble, chemical reaction is initiated leading to high local pressure peaks and gas luminescence. At sufficiently high void fractions, these local pressure peaks induce further reactions in neighbouring bubbles and cause a self supporting steady soliton like wave in a column of bubbly liquid.

By superposition of several waves an experimental averaging was performed which allowed to extract a profile suitable for quantitative comparison. The influence of void fraction, bubble size, and gas composition upon wave shape and speed will be discussed, and some properties of the theoretical modeling of the system as well as the comparison of theory and experiment will be reported.

Experimental investigation and computer analysis of spontaneous condensation in stationary nozzle flow of CO_2/air mixtures

K. Bier, F. Ehrler, M. Niekrawietz

Institut für Technische Thermodynamik und Kältetechnik, Universität Karlsruhe (TH)

The influence of an admixture of air on the onset and the progress of spontaneous condensation of carbon dioxide in a stationary supersonic nozzle flow has been studied for mixtures with CO_2- mole fractions ranging from 5 to 75 per cent. For mole fractions of 75 and 50 per cent, the supersaturation of the carbon dioxide at the Wilson point is not influenced by the addition of air. In the range of lower CO_2-concentrations, the condensation of carbon dioxide is promoted by the presence of the non-condensing component, as was to be expected from various results reported in the literature.

The thermodynamic state in the Wilson point and the progress of the static pressure in the partially condensed flow were calculated with the Oswatitsch formulation of the condensation process based on the classical nucleation model and on a formulation of droplet growth given by Gyarmathy. It is remarkable that the results of the calculation, obtained with a uniform choice of the free parameters of this condensation model, agree well with the experimental results, both for pure CO_2 and for CO_2/air mixtures.

Spontaneous condensation in stationary nozzle flow of carbon dioxide in a wide range of density

K. Bier, F. Ehrler and G. Theis

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Universität Karlsruhe (TH)

The onset and the progress of spontaneous condensation in a supersaturated, supersonic nozzle flow of carbon dioxide has been investigated by precise measurement of the static pressure along the nozzle axis. The supersaturation at the Wilson point, where condensation begins, has been measured from pressures below the triple point up to about 90 per cent of the critical pressure. The Wilson line obtained in this way for expansions performed with the same nozzle is compared with similar results for two refrigerants, CHF_2Cl and CF_2Cl_2, and for water vapour. The Wilson lines of carbon dioxide and of the refrigerants are nearly identical in a normalized pressure, temperature-diagram.

EFFECT OF THERMODYNAMIC DISEQUILIBRIUM ON CRITICAL LIQUID-VAPOR FLOW CONDITIONS

Z. Bilicki and J. Kestin

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Polish Aacademy of Sciences, Gdansk, Poland

Abstract

In this lecture we characterize the effect of absence of unconstrained thermodynamic equilibrium and onset of a metastable state on the adiabatic flow of a mixture of liquid and its vapor through a convergent-divergent nozzle. We study steady-state flows and emphasize the relations that are present when the flow is choked. In such cases, there exists a cross-section in which the flow is critical and in which the adiabatic wave of small amplitude is stationary. More precisely, the relaxation process which results from lack of equilibrium causes the system to be dispersive. In such circumstances, the critical velocity is equal to the frozen speed of sound, a_f corresponding to

The relaxation process displaces the critical cross-section quite far downstream from the throat and places it in the divergent portion of the channel. We present the topological portrait of solutions in a suitably defined state-velocity space and discuss the potential appearance of normal and dispersed shock waves. In extreme cases, the singular point (usually a saddle) which enables the flow to become supercritical is displaced so far that it is located outside the exit. Then, the flow velocity is everywhere subcritical ($w < a_f$) even though it may exceed the equilibrium speed of sound (w a_e) beyond a certain cross-section, and in spite of the presence of a throat.

Cavitation behind tension waves

J. Bode, G.E.A. Meier and M. Rein
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Spontaneous cavitation in liquids can be produced by strong tension waves. Tension waves can be generated by the reflection of expansion waves at a solid wall. Experimental observations of wave phenomena related to tension waves are performed in a tube with a free surface on one end and a solid wall on the other end. The propagation of the tension wave and the extension of the resulting cavitation bubble field are observed by pressure measurements and high speed photography. The interaction between the cavitation bubbles and the reflected waves in the tube causes periodically generated bubble fields. Experimental results can partly be compared to numerical simulations based on the microbubble - model of Rein and Meier. Among other things a physical explantion for pressure oscillations in the bubble field can be given and a model for the interaction of cavitation bubbles is supposed.

INVESTIGATION OF NONEQUILIBRIUM GRAVITATIONAL EFFECT NEAR THE CRITICAL POINT BY INTERNAL GRAVITATIONAL WAVES

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ABSTRACT

The structure and dynamics of adiabatic internal gravitational waves in a vapour-liquid system near the thermodynamic critical point are investigated theoretically and experimentally. Two cases and two types of internal waves are studied. The first case is when substance is stratified and there is a sudden shock wave with infinitesimal thickness of the "liquid-vapour" boundary. Such density distribution exists at critical isochore up to the temperatures $|T_c - T| / T_c > 3 \cdot 10^{-3}$. The internal waves propagate along the "liquid-vapour" interface. The second case is when substance has continuous density distribution from liquid to vapour phases at $\Delta T/T_c \leqslant 3 \cdot 10^{-3}$. In this case short internal waves occur, whose phase surfaces are mutually intersecting planes located at an angle to the pycnocline axis which are of the "cross" type similar to hydrochloric solutions.

The relaxational processes of density change at the parameter variation of the system phase equilibrium are studied with the help of short internal waves. The singular behaviour of relaxational time, when approaching the critical point, is found.

An equation describing the dynamics of internal waves in

pycnocline near the critical point is obtained. The relation between critical indices of thermophysical substance properties, velocity and structure of internal waves is shown theoretically and experimentally. The possibility to study the thermophysical properties of substance in the vicinity of critical point using the wave methods is demonstrated.

Properties of kinematic waves in two-phase pipe flows

J.A. Bouré

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Service d'Etudes Thermohydrauliques
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Abstract

In two-phase pipe flows, the slip velocity or, equivalently, the drift flux (volumetric flow rate of the "light" phase in a reference frame moving with the center-of-volume velocity) is related to the void fraction. This is typical of situations leading to the appearance of kinematic waves (Whitham, 1974, Zuber, 1961).

Waves, including kinematic waves, play a crucial role in controling the system behavior, and no model can be satisfactory if the relevant propagation phenomena are not correctly described. Kinematic waves convey void fraction and density signals and they most probably control flow-pattern transitions.

Kinematic waves have been investigated experimentally in air-water two phase flows by inducing small void fraction disturbances at the inlet of vertical ducts, the average void fraction varying from .01 (bubbly flows) to .41 (slug flows). The temporal fluctuations of the void fraction are detected in regularly spaced cross sections by non-intrusive impedance probes.

The statistical processing of the data reveals the existence of two kinematic modes and provides their velocities and damping (or amplification) coefficients. The results are presented and discussed. One of the modes, practically absent at low void fractions, is predominant at larger void fractions. As the void fraction increases it changes from damped to amplified and controls the bubble-slug transition.

Acoustics of travelling bubble cavitation

J. Buist
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University Twente
The Netherlands

Abstract.

Experiments on cavitation prove that the noise level is highly dependent on the type of cavitation. Usually it is expected that bubble cavitation is much less severe than cloud cavitation. To verify this expectation, noise measurements on a bubble stream over a hydrofoil were done at Marin (Wageningen ,The Netherlands). These experiments show that there is not much difference irrespective of the fact whether the bubbly flow is clustering or not.

In this paper the noise level produced by a macroscopically steady bubbly layer on a hydrofoil is predicted analytically, based on the stochastic properties of the fluctuating quantities in the layer. This analysis uses the technique of Fourier-Stieltjes transformation as used by O.M. Phillips. In this way, the sound spectrum outside the bubble layer can be correlated to the covariance of the fluctuating quantities, as gasfraction, velocity etc. ,assuming for instance that the bubble layer is stochastically stationairy and almost homogeneous.

Based on this theory a decision can be made what the relative importance is of cluster formation, in dealing with the sound production of bubble layers.

EVAPORATION WAVES IN LIQUIDS OF HIGH MOLAR SPECIFIC HEAT

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Fluids of high molar specific heat are usually organic substances composed of molecules with a large number of atoms and consequently a large number of internal degrees of freedom. Complete adiabatic phase transitions of these fluids can occur in flows and waves at high temperatures because then the energy storable in the molecules exceeds by a large margin the energy involved in the phase transition. For complete evaporation by adiabatic expansion the liquid has to be heated to such an initial temperature that the heat of evaporation is available in the internal energy. Experiments were carried out to observe this case starting from an intially saturated liquid state. The phenomena observed after an initial superheat of the liquid introduced by expansion are nucleation, wave-splitting and evaporation waves. The evaporation waves behave analogously to deflagration waves well known from literature. Therefore a comparison of the experimental results obtained for the waves with phase transition can be done with the theory of normal shocks.

MODELLING OF FINITE LIQUID VOLUMES UNDER SHOCK LOADING

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Siberian Division of the USSR Academy of Sciences
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ABSTRACT

Cavitation evolution dynamics in cylindrical liquid volumes under the axial loading by an exploding wire is studied experimentally and theoretically. The method of dynamic head registration is used to study the structure of two-phase flows formed and evaluate characteristic time of cavitation liquid fracture. As a result of numerical simulation of the experiments, which was performed in a single-velocity two-phase model approximation, the energy transformation mechanism is determined at shock interaction with a free real-liquid surface. A two-phase model is suggested to describe the irreversible development of a cavitation zone formed as a result of the mentioned interaction. The model is based on practically instantaneous tensile-stress relaxation in a centered rarefaction wave and the further inertial evolution of the process.

AN ASYMPTOTIC PREDICTIVE METHOD FOR GAS DYNAMICS WITH NONEQUILIBRIUM CONDENSATION

Can F. Delale

Department of Mathematics

Boğaziçi University

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ABSTRACT

An asymptotic method for quasi-one-dimensional nozzle flows with nonequilibrium condensation that reveals the structure of possible condensation zones is presented as developed in [1]. The streamtube formulation for expansion flows on walls with nonequilibrium condensation employed with the asymptotic method is discussed for both smooth flows and flows with an embedded, frozen, oblique shock wave as developed in [2]. In particular the location of the oblique shock waveis predicted by employing Barschdorff's shock fitting technique [3] . A simple numerical experiment for Prandtl-Meyer flow is presented to demonstrate the usefulness of the method and to give a comparison with the widely used numerical method of characteristics. The extension of the method for shock tubes is also summarized.

[1] J.H.Clarke and C.F.Delale. Phys. Fluids 29(5) 1398 , ibid 1414 (1986).

[2] J.H.Clarke and C.F.Delale. Quart. Appl. Math. Vol. XLVI, No. 1 , 121 (1988).

[3] D.Barschdorff. Forsch. Ingenieur Wes. 37, 146 (1971).

EFFECT OF ULTRASOUND POWER ON SPECTRAL DISTRIBUTION AND SONOLUMINESCENCE INTENSITY OF WATER

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Far East Branch of the USSR Academy of Sciences
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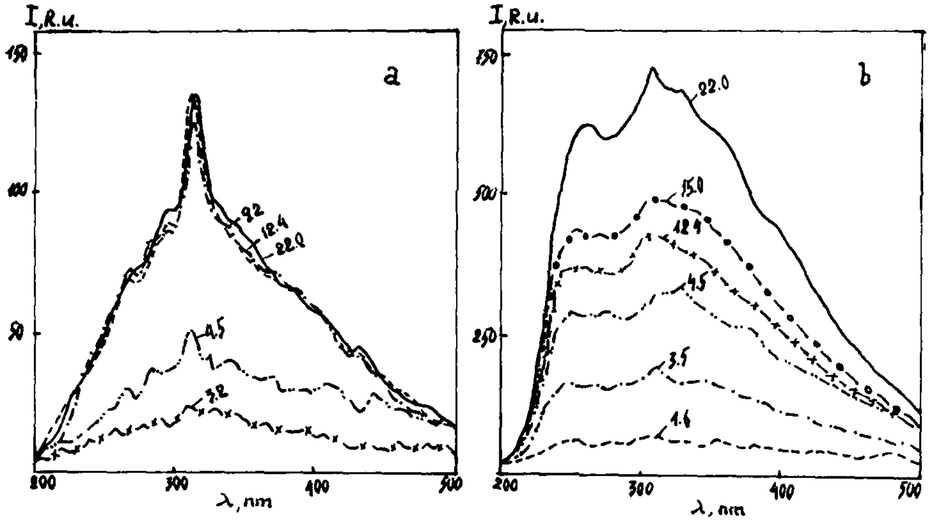
ABSTRACT

Sonoluminescence is a weak emission of light observed in cavitating liquid. The mechanism of this complex phenomenon is not clearly understood. The purpose of this report is to examine the sonoluminescence spectra of water in the presence of argon and xenon and its changing with ultrasound power.

Sonoluminescence spectra of the Ar- and Xe-saturated distilled water were measured with the same procedure as discribing in [1]. The irradiation plexyglace cell (diameter - 2cm, volume - 45 cm^3) was termostated by 19±1°C. The source of ultrasound was 22 Kc, 1 cm diameter titanium horn.Emitted light passed into monochromator MDR23 with 0.22 cm slit through quartz window and was detected with photomultiplier PEM100-tube. Spectra were collected with 2 nm increments in 200÷500 nm interval. The conditions of recording and treatment of all spectra were controlled by computer. The power of ultrasound was determined calorimetrically. Sonoluminescence spectrum of argon-saturated water is the same as in [1,2](fig.a), but the spectrum of the xenon-saturated water has a strong band near 260 nm (fig.b),that can not be detected in [2] because the region less than 270 nm was not explored. This band may be attributed to the emission from water molecules in excited states or recombination processes with light radiation but this assumption is requiring experimental investigation.

The fact that sonoluminescence in Xe-saturated water is



The sonoluminescence spectra of water in the presence of argon (a) and xenon (b) with different ultrasonic powers (W/cm^2).

stronger as in Ar-saturated is in accordance with [2] and it is explained with differences in their coefficients of thermal conductivity. Sonoluminescence intensity of Xe-saturated water grows through all the intervals of powers P used which is not in the case of Ar-saturated water (fig.a,b). The possible explanation is that with P more than 9,2 W/cm^2 the number of cavitating bubbles can not rise and it is pointed out with invariable of sonoluminescence intensity in Ar-saturated water (see fig.a). But energy of single cavitation bubble implosion grows with P because of rising sonoluminescence intensity in Xe-saturated water.

We believe that equilibrium state between the heating processes of the bubble's content due to compression and its cooling due to thermal conductivity is achieved by higher temperature with Xe, than with Ar-content bubbles. Consequently one can receive much higher temperatures and intensities of light emission for the Xe-saturated water than for Ar-saturated water.

The sonoluminescence spectra are not changed in our experi-

ments probably due to invariability of electronic-states transformation of atoms and molecules in cavitation bubble for given frequency and powers of ultrasound.

1. C.Sehgal, R.G.Sutherland, R.E.Verral. J.Phys.Chem.,1980,84,4, 388-395.
2. K.T.Taylor, P.D.Jarman. Aust.J.Phys.,1970,23,3,319-334.

GENERALIZED DIFFUSION THEORY OF BUBBLY AIR - WATER TWO - PHASE FLOW

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National Center for Scientific Researches
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The problem of bubbly air - water two - phase flows is attracting the great attention of scientists. One of the most important and comlicated aspects of these flows are the lateral phase distribution mechanisms. Many experimantations show that for up flow in a circular test section the bubbles tend to migrate toward the wall and thus the viod fraction profile has a distinct peak near the wall. In constrast for down flows the bubbles tend to migrate toward the center of the pipe.
Some theoretical models of bubbly air - water two - phase flow have been constructed, but no one is able to predict satisfactory lateral phase distribution. In this paper the author is undertaking one attempt to theoretically describe these phenomena. The bubbly air - water flow is considered as a two - phase flow with microstructure. In contrast to multivelocity theory of multiphase flows, instead of using a conception of phase velocities and constructing a equations system to determine all of them, here some general characteristic velocity of the multiphase continuum as a whole is introduced, the relative motion of phases with respect to this velocity is determined as the generalized diffusion fluxes. A closed system of equations is obtained to determine these unknown and bubble microdeformation. It is shown that exists a good agreement between the theoretical and experimental results.

Vapor Detonations in Superheated Fluids

G. Richard Fowles
Washington State University

We describe numerical simulations of one-dimensional flows that illustrate the development and structure of vapor detonations in superheated fluids. Such detonations are nearly always weak detonations independent of the rate of transformation from liquid to vapor because of the marked difference between liquid and liquid-vapor mixed phase Hugoniot curves. This behaviour contrasts with that generally accepted for chemical explosives which, because of presumed slow reaction rates, are thought to support only strong or Chapman-Jouget detonations. Because weak detonations are supersonic with respect to both the flow ahead of and behind the detonation front, the stability of such flows cannot be treated with theories developed for shocks in inert substances; for those the shock velocity is necessarily subsonic with respect to the downstream flow. Numerical studies of instabilities of weak detonations will be presented.

PROPAGATION OF A VAPOR EXPLOSION IN A CONFINED GEOMETRY

D. L. Frost, G. Ciccarelli, and C. Zarafonitis
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McGill University, 817 Sherbrooke St. W.,
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ABSTRACT

The propagation of a vapor explosion within a narrow channel (1.27 cm width) has been investigated experimentally for three different systems: (i) a linear array of molten tin drops immersed in water, (ii) a stratified mixture of molten tin and water, and (iii) a coarse mixture of freon-114 droplets in ethylene glycol. In each system, the hot liquid is initially separated from the cold liquid by stable vapor film(s). The vapor explosion is initiated by a shock wave generated by spark discharge. Spatial propagation of the explosion occurs over a narrow range of liquid temperatures. In each case, the explosive interaction propagates as a front with a typical velocity of 40-60 m/s. The pressure rise associated with the front has a peak overpressure in the range of 4-8 bar. The low propagation velocity and relatively long pressure rise times (~1 ms) indicate that the propagation is not coupled to the initial triggering shock. With multiple molten tin drops immersed in water, spatial propagation of the interaction is due to sequential explosion of the drops. The pressure rise and associated convective flow generated during the expansion of the steam explosion bubble due to one drop is sufficient to destabilize nearby vapor films, initiating liquid-liquid contact and the explosion of an adjacent drop. A similar propagation mechanism is observed in the freon/ethylene glycol system, although the volume of vapor initially present is considerably larger. In the stratified molten tin/water system, the explosive interaction propagates along the surface of the tin, producing a wedge-shaped wake of vapor. Only a small fraction of the tin participates in the explosion, and the majority of the tin is lofted in the wake. The average mixing depth was estimated to be 1.4 mm based on post-trial debris analysis. The explosion appears to propagate in a quasi-continuous manner, consisting of a sequential series of local explosions along the top surface of the tin.

DETERMINATION OF CONDENSATION PARAMETER OF VAPOURS BY USING A SHOCK-TUBE

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ABSTRACT

Non-equilibrium condensation of vapour on the condensed phase is one of the most fundamental problems of fluid dynamics in the sense that it must be treated on the level of molecules from both aspects of gas and liquid states.

In order to determine condensation parameter of vapours, shock-tube has been applied. The growth process of liquid film on a shock-tube endwall behind a reflected shock wave has been measured by an optical method based on mutiple reflection of light in the film. The result has been compared with the theoretical one using molecular gas dynamical boundary conditions. Our previous theoretical prediction (Fujikawa et al. 1987) of a transition phenomenon during the growth of the film has experimentally been demonstrated: the film grows approximately in proportion to the time at early stages after the reflection of the shock wave and, after some transition period, it grows in proportion to the square root of the time. The values of condensation parameter of methanol and water vapours have been determined from the conformity between the experiment and the theory. The measured values have been found to be 0.04 for methanol vapour and 0.11 for water vapour and have theoretically been explained by statistical mechanics of gases and liquids.

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FILM BOILING PHENOMENA IN LIQUID-VAPOR INTERFACES

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ABSTRACT

The equations of motions for a fluid whose internal energy is a function only of density, entropy and their spatial derivatives are able to explain motions through non-isothermal liquid-vapor interfaces* .

Then, molecular and statistical models are presented, which take the local state of molecules into consideration and lead to the internal energy of the fluid.

An interpretation of *film* boiling phenomena (A liquid is on a very hot plate and sustained by a vapor layer) is obtained: a liquid bulk, a very thin interface, a film of vapor when the density ρ decreases a little bit until ρ reaches the value for which temperature is equal to that of the plate. That leads to the evaluation of the temperature from which the film boiling occurs: Leidenfrost's temperature.

In the case of Van der Waals fluids a numerical analysis gives a maximum flow for a fixed pressure in the liquid bulk. At any pressure and temperature, flows have an absolute maximum. A temperature is associated with a maximum flow. This temperature is interpreted as the temperature that Boutigny wrote about** .

It is possible to extend these results for mixtures of fluids. It may give a better understanding of the burnout phenomena which is source of annoyance for nuclear engineering and metallurgy.

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STATIONARY AND MOVING NORMAL SHOCK WAVES IN WET STEAM

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ABSTRACT

Steam of low wetness fraction (< 20%) is a dispersive medium and two distinct limiting sound speeds can be identified corresponding to complete equilibrium and fully frozen flow respectively. A stationary normal shock wave in wet steam can therefore exhibit either a fully dispersed or a partially dispersed structure depending on the velocity of the upstream flow. A theoretical analysis of the structure of such shocks clearly demonstrates the role of the three different time scales associated with the various relaxation processes occurring within the wave. In contrast, the internal structure of a moving shock wave can change with time. A time-marching computational method for unsteady condensing flows has been developed and has been applied to solve the classical piston and cylinder problem for wet steam where the piston is accelerated impulsively to a constant velocity. Initially the shock wave generated is discontinuous but, as the relaxation zone behind the wave develops, the shock weakens until an equilibrium structure is attained. The results have a direct bearing on the periodically unsteady flow of a condensing medium in a converging-diverging nozzle and the non-equilibrium two-phase flow in low-pressure wet-steam turbines.

LIQUEFACTION SHOCKS AND RAREFACTION WAVES IN RETROGRADE AND REGULAR FLUIDS WITH DOWNSTREAM STATES NEAR THE LIQUID–VAPOR THERMODYNAMIC CRITICAL POINT

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ABSTRACT

Near–critical downstream states are produced from a single-phase initial state (superheated vapor) by means of reflection of a liquefaction shock (retrograde fluids), or by means of reflection of a rarefaction wave (regular fluids) from the shock tube endwall.

Numerical computations to predict the necessary conditions leading to a downstream state which is precisely at the equilibrium critical state requires an accurate equation of state which, in addition to representing the thermodynamic behavior of pure fluids in the entire fluid range, describes the transition from the nearly–horizontal course of the critical isotherm to the supercritical liquid and vapor states. Furthermore, the extent to which the downstream state satisfies the equilibrium Rankine–Hugoniot conditions is of extreme importance.

Whether the fluid is nearly in equilibrium, or not, depends heavily upon a settling time which increases with the proximity to the critical point. The great disparity of time scales in the near–critical region suggests the use of molecular dynamics to simulate the flows described above in retrograde fluids which have a complex molecular structure.

AN INVISCID APPROACH TO PHASE TRANSITION PROBLEM

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ABSTRACT

In this talk I would like to summarize the possible usefulness of the entropy rate admissibility criterion proposed by Dafermos for a van der Waals type fluid which exhibits the phase transition. The above criterion roughly says that the entropy increases with the highest rate for the admissible solution. I would like to apply this criterion to the isothermal and nonisothermal cases. I would like to consider the Riemann problems in which we specify two different constant states in the different phases as the initial data and show, among other things, that the stationary phase boundary which satisfies the equal area rule (the Maxwell line construction) minimizes the above criterion in a small class of solutions.

AN EXPERIMENTAL STUDY OF EVAPORATION WAVES IN A SUPERHEATED LIQUID

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The dynamical behavior governing the propagation of evaporation waves has been studied using a volatile fluorocarbon in a facility utilizing a constant diameter, vertical glass test cell situated beneath a large, low-pressure reservoir. Of particular interest are the physical mechanisms by which a pure liquid is fragmented into an aerosol, thereby rapidly releasing its stored thermal energy to phase change and kinetic energy. It is observed that, provided care is taken to suppress *all* nucleation within the liquid, acoustic waves depressurize the liquid to virtually the ambient pressure before eruption of the liquid at the free surface raises it to a higher value which is maintained for the duration of the run. Within several milliseconds of the initial eruption, a steady-state process is achieved in which a fragmentation/acceleration region (wavefront) propagates into the stagnant liquid, producing a high-speed aerosol flow behind it. Thermodynamic conditions are not such that the spinodal curve is reached at any time during the run; consequently, homogeneous nucleation is not observed. Rather, high speed, high resolution motion pictures indicate that the wave propagates via a heterogeneous nucleation process: the leading edge of the wavefront consists of a sheet of smooth "bubbles", the thickness of which is limited to a few millimeters by a vigorous bursting process. Thus, the interstitial liquid between bubbles is observed to be fragmented into droplets in a nonsteady manner. The region in which bursting and fragmentation takes place is about one centimeter in extent; most of the flow acceleration also takes place there due to the large increase in surface area and hence evaporation rate. It is interesting that this flow is both steady and nonsteady: for time scales significantly greater than the characteristic bubble lifetime (about one millisecond), flow properties such as wavespeed and pressure are remarkably constant; meanwhile, on time scales of the same order as the bubble lifetime, nonsteady processes (nucleation and bursting) are at work which generate the mean flow.

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HYDRODYNAMICS OF EXPLOSION: EXPERIMENT AND MODELS

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Hydrodynamics of high-speed processes is associated with a wide class of nonstationary phenomena developed in liquid under pulse loading. A particular concern is given to effects owing to evolution of bubble cavitation that is due to tensile stresses arised in liquids, for example, under the interaction of shock waves and a free surface. Cavitation develops on microinhomogeneities in the rarefaction wave in the form of a cloud of expanding bubbles. The cloud is often called as a bubble cluster.

The paper considers the effects of evolution and collapse of cavitation clusters in the region between a radiator and immovable solid surface (cavitation erosion) and also at the bottom of a shock-accelerated tube filled in with liquid. The problem is studied within the framework of a general approach based on the non-equilibrium two-phase model. Such an approach allows us not only to solve a series of principal problems, concerned with a bubble cluster dynamics, and also to calculate the structure and parameters of a wave field in the region of developing cavitation. Description of a new evolution mechanism of dense bubble clusters is given. The structure peculiarities of pulse rarefaction waves are discussed. The effect of size distribution of cavitation nuclei is shown.

VAPOR CONDENSATION BEHIND A SHOCK WAVE PROPAGATING THROUGH VAPOR-LIQUID TWO-PHASE MEDIA

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ABSTRACT

A vapor condensation phenomenon behind a shock wave propagating through two-phase media with large quality (vapor to fluid mass ratio) was investigated experimentally by using shock tube facility. The obtained results of the vapor flow field indicate large difference in the process of attaining thermal equilibrium condition from those of ideal gas represented by Rankine-Hugoniot relation. In the former shock intensities generated are much weaker, and larger heat energy are transferred to the tube wall surface. A series of schlieren photographs taken by the high-speed drum camera illustrate a sequential change of generation, growth and evaporation of fluid condensates on the wall surface. These imply the existence of phase change phenomenon caused by thermo-fluid dynamic behavior of the vapor, the relaxation time of which is in orders of magnitude longer than that predicted by one-dimensional analyses developed by Marble and others. It seems that heat transfer in the boundary layer created from behind a shock front has strong effects on the rate of phase change of the working fluid in such a flow field.

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LIQUID-VAPOR PHASE CHANGE AND SOUND ATTENUATION

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ABSTRACT

Starting fom the entropy produced at the liquid surface the transport matrix for the heat and mass transfer is derived. Onsager symmetry and the role of the condensation coefficient, the evaporation coefficient and the energy accomodation coefficient is discussed. Furthermore, the connection between these coefficients and the gas-surface scattering of the molecules is represented.
Based on the acoustic equations, Millikan's formula for the drag of droplets and the transport matrix for the heat and mass transfer, a numerical solution for the sound attenuation is given and the influences of droplet size and the evaporation coefficient are discussed. A simplified relationship for the sound damping is suggested which is in good agreement with the numerical solution.
The reflectance r of a liquid surface for sound incident from a saturated vapour depends on the evaporation coefficient, which offers a direct possibility of measuring this coefficient. The dependence of the reflectance on the nature of the substance, the evaporation coefficient and the sound frequency is discussed.

SHOCK WAVE PROPAGATION IN LOW TEMPERATURE FLUIDS AND PHASE CHANGE PHENOMENA

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ABSTRACT

In the fields of physical chemistry, aerospace science, and industrial engineering, many kinds of fluids are utilized, most of which have their point of phase change below the room temperature to cryogenic range. With the progress of cryogenic technology, unsteady multiphase behavior of low temperature fluids with high velocity has been an important objective that should be clarified. This work deals with the shock wave experiments in low temperature gases by means of diaphragmless (snap-action) shock tube combined with the cooling by liquid nitrogen. Together with the normal gases of N_2 or O_2, the refrigerant R-12 (Freon-12, CCl_2F_2, atmospheric boiling point; 243.5K) is used as a test gas. Shock wave propagation and reflection from the end wall, liquid R-12 free surface, and 2-dimensional wedge are investigated. Nonequilibrium condensation at the cold tube wall behind the propagated shock wave in R-12 is observed by flow visualization techniques by pulse light and high speed frame camera. For the flow field around the 2-dimensional wedge behind the shock propagation, simple estimation for the oblique shock relations including the condensation effect is conducted, and the obtained results are discussed as compared to the usual oblique shock waves. The phase change phenomena in low temperature fluids are discussed, along with the vapor bubble collapse observed in our shock-compressed R-12 liquid phase.

UNIVERSAL BUBBLE SIZE DISTRIBUTION IN INSONIFIED LIQUIDS

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The acoustic stable cavitation is known to be accompanied by the appearence of gas bubble clouds. The bubbles of visible sizes grow from microbubbles by rectified diffusion and microstreaming mass transfer. As the bubble grows it decreases the concentration of dissolved gas in the more and more extended area. The process taking place under the intersection of domains deserted by the close bubbles does not correspond to the customary model of independant nuclei and it is necessary to take into consideration diffusive interaction between the bubbles.

We shall consider the model of selfconsistent field when each bubble is influenced by the average concentration of dissolved gas $\bar{C}$ and this now varying quantity will be defined by the total bubble ensemble. The mass conservation law connects the average concentration of dissolved gas to the number of gas molecules in the bubbles. The growth of a single bubble is governed by the equation which conserves its customary form (Crum et al, 1982) but the constant value of concentration far from the bubble C_∞ is replaced by the varying average value $\bar{C}(t)$. The partial differential equation describes the evolution of the bubble size distribution $g(R,t)$ with time

$$\frac{\partial g}{\partial t} + \frac{\partial}{\partial R}(v_R\, g) = 0$$

where $v_R = \dot{R}$, R - bubble radius.

Consider the special case (Maksimov, Polovinka, 1987) when the dominant process of rectified diffusion has the same effect as the gas supersaturation of liquid. This is the case

when the Lifshitz-Slezov theory of coalescence may be used and the following results derived: the asymptotic (with time) form of bubble size distribution, the power law of bubble number andthe average gas content reduce. Note, that this solution is automodel in nature and thus the bubble size distribution is universal and it does not depend on initial distribution.

In the general case gas flow in (or out) a single bubble depends on two consequent processes of absorption (or emission) of gas molecules by the bubble surface and diffusive or convective mass transfer. Accounting of these two processes of nonequilibrium surface kinetics and microstreaming mass transfer does complicate the description of bubble evolution.

Nevertheless, one can derive asymptotic bubble distribution under the condition that rate of mass transfer is governed by surface kinetics. The form of this distribution is similar to that of the nuclei in the theory of coalescence when the dimentioality equals two.

Using the new theoretical results (Tur et al, 1988) one can also get universal asymptotics in the space of sizes. For dominant process of rectified diffusion we have $g(R,t) \sim$ $\sim R^2$ in the range of small sizes ($R \to 0$) and $g(R,t) \sim R^{-7}$ on the transformational interval. For dominant surface kinetics we have $g(R,t) \sim R$, $R \to 0$ and $g(R,t) \sim R^{-5}$ on the transformational interval.

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THE DEVELOPMENT OF CAVITY CLUSTERS IN TENSILE STRESS FIELDS

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ABSTRACT

The development of a cavity cluster from a distribution of supercritical cavitation nuclei at their exposure to tensile stress is discussed. An approach to this problem was presented for one–dimensional clusters by Hansson et.al. (1982), and is the basis of further analysis and comparison of one–dimensional and spherical cavity cluster development. In a cavitating medium $\partial p/\partial \rho < 0$ so that low–frequency disturbances are not propagated, but the boundary of a cluster of cavities exhibits an acoustic impedance connected to the cavity dynamics, which determines the reflection and transmission conditions of an ambient wave field. The dynamic effects spread from the boundary into the cluster. At compressive external stress the cavities forming the instantaneous cluster boundary successively collapse and the equations of the propagating collapse wave determine the impedance of the cluster boundary (Mørch 1989). At tensile stress the cluster boundary essentially remains fixed in space while an increasing number of cavities participate in the void expansion and cause a low acoustic impedance at the cluster boundary. For a spherical cluster of cavitation nuclei a focussing effect and the finite cluster dimension govern cavity growth throughout the cluster.

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WAVE PROPAGATION IN FLOWING BUBBLY LIQUID

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ABSTRACT

Propagation characteristics of waves out of a source placed in uniform flow are discussed on the basis on the dispersion relation for a rarefied bubbly liquid model. Because the propagation velocity is different depending on the wavenumber, the propagation direction is reversed at a certain wavenumber and there appear strongly damping modes.

In order to make clear the properties of those waves, particularly the unusual waves which appear within a certain range of frequency and which result from the interaction between the volume oscillation of bubbles and the wave motion in the flowing medium, and to find the fraction of energy disappearing with damping waves, the exact solution of the initial-boundary value problem is derived for the waves caused by imposing small sinusoidal disturbance at a location in the uniform main stream from an initial time. The solution shows the change of each mode and the energy distributed to each mode, depending on the Mach number in the main stream and the outgoing direction, as the frequency of the source is increased. When the Mach number is low and the outgoing direction relative to the flow is large, most disturbance of high frequency is damped and there is a little propagation wave.

Pressure fluctuation characteristics of bubbly liquid flows observed in converging-diverging nozzle and in riser, particularly the disappearance of intermediate frequencies in PSDF, is interpreted by the above theoretical results. The possibility is demonstrated that the energy absorbed to the damping waves has been expended to break up bubbles.

NONSTATIONARY WAVE PROCESSES IN BOILING MEDIA

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ABSTRACT

Boiling medium is a typical example of heterogeneous multiphase medium with various internal structure. Modelling the wave processes in such medium will be difficult due to the complex nature of mass power and energy interaction at a "vapour-liquid" interface. However the basic effects governing the formation and motion of compression waves in such medium can be obtained considering this medium as a superposition of the most characteristic flow regimes and analyzing the wave processes in these regimes. This lecture considers the models of compression wave propagation at different structures of two-phase flow and outlines the general mechanisms of wave formation for all the structures, the scope of these mechanisms and, finally, the basic peculiarities of the propagation of strong compression waves.

ON THE MACROSCOPIC BOUNDARY CONDITIONS AT THE INTERFACE FOR A VAPOUR-GAS MIXTURE

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ABSTRACT

Motions of a binary gas mixture of a vapour and an inert gas in a general domain are investigated on the basis of kinetic theory. The analysis has been carried out under the assumptions: 1) the deviation of the system from a certain stationary equilibrium state is small; and 2) the Knudsen number, the ratio of the molecular mean free path of a vapour to a characteristic length of the system, is small but is of the order of the deviation. In this case, the Reynolds number of the system is of order unity, since, in general, it is proportional to the ratio of the Mach number to the Knudsen number, where the Mach number is a measure of the magnitude of the deviation. The macroscopic equations and the boundary conditions appropriate for them together with the Knudsen-layer corrections near the interface are derived in general terms. The macroscopic equations obtained are of Navier-Stokes type in the present case, and the macroscopic boundary conditions are given in terms of slip in velocity and jumps in temperature and partial vapour pressure. The Knudsen-layer corrections are to be applied within a layer of the order of the molecular mean free path called the Knudsen layer formed near the interface to obtain the uniformly valid solution to the kinetic equation. The derived system of macroscopic equations and boundary conditions makes possible at the level of ordinary fluid dynamics the treatment of various problems of a binary gas mixture which require kinetic theory consideration, giving adequate description of the behaviour of a mixture and its component gases. Although this macroscopic system is not meant for unsteady problems, it may give, as far as the boundary conditions are concerned, the appropriate conditions for such problems at the interface(s) between the condensed phase(s) and the gas phase.

VAPOR-LIQUID PHASE CHANGE STUDIED BY MEANS OF A SHOCK TUBE EXPANSION-COMPRESSION PROCESS

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ABSTRACT

We investigate the vapor-liquid phase transition initiated by homogeneous nucleation in the supersaturated state of a vapor. The vapor is carried in an inert gas which is subjected to a transient expansion-compression process in a shock tube. The reflected finite expansion of the driver section serves to transfer the vapor rapidly into a desired supersaturated state. A subsequent weak shock wave is generated to limit this state to a fraction of a millisecond. Nuclei are born in this state which grow into droplets as long as supersaturation persists. With the nucleation period very short and the growth period much longer the nuclei develop into a cloud of monodisperse droplets.

The growing monodisperse droplets lend themselves to detection by Mie-light scattering which is set up by a laser and a photomultiplier in a 90° scattering mode.

The principal topics of investigation are the production rate of droplets, the rate at which mass is accomodated by the droplets (growth) and the rate of reevaporation due to shock wave heating. It is intended to report on findings concerning the mass accomodation problem in the case of water carried in argon.

A Simple Discrete Kinetic Model Resembling Retrograde Gases

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A retrograde gas is a complex medium which exhibits very unusual properties [1]. Being however convinced that one can understand even complicated phenomena by means of simple mathematical models we propose a model of kinetic character which has some properties typical for retrograde gases. We take into account binary and ternary collisions. The characteristic feature of the model is that the probabilities of direct and inverse collisions are not symmetric. Owing to that the equilibrium distribution is not a Maxwellian. With this model we study the plane shock wave structure. The equation we derive is the same as the one obtained by Cramer and Kluwick [2]. The shock wave thickness expressed in mean free path is larger than that in regular gases, what agrees with the recent experimental results of [3]. We find also that in some cases the number density must decrease in order for the shock to be stable. Thus our model admits solutions typical for retrograde gases.

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A QUALITATIVE THEORY OG LIQUEFACTION SHOCKS

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We present a qualitative theory of liquefaction shocks in retrograde fluids which is analogous to the classical Zeldovich - von Neumann - Doering theory of detonation. The key ingredient of our theory is the sonic interpretation of spontaneous condensation metastable states (Wilson's states). In the framework of the qualitative theory, a consistent treatment of shock splitting is developed and links to endothermic detonations with reversable chemical kinetics are discussed. The results are obtained in a joint work with A. Majda of Princeton University.

A numerical study of nitrogen condensation in 2-D transonic flow in cryogenic wind tunnels

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To increase the Reynolds number cryogenic wind tunnels operate with pure nitrogen which is cooled down to about 100 K and pressurized from 4 to 9 bar. Local accelerations in the test section, producing additional supercooling, e. g. around airfoils, may cause condensation onset. Measured datas of pressure, drag and lift may become unusable.

We investigate 2-D transonic flow of pure nitrogen at the most critical stagnation conditions (highest pressure and lowest temperature) and with **realistic cooling rates** -dT/dt of about 0.02 - 0.03 K/μs which are typical in **transonic** test cases. For the first time inviscid stationary 2-D flows of nitrogen with nonequilibrium phase transition are investigated numerically using the Euler equation coupled with the classical nucleation theory of Volmer. The droplet growth rates are calculated using the macroscopic law of Oswatitsch (droplet radius greater than the mean free path) and the surface averaged radius of Hill. Real gas effects are not yet included. In the limitations of the conditions for pressure and temperature **transonic onset** Mach numbers $M_c < 1.3$ are achieved. A detailed analysis of the 2-D structure of the pressure disturbances will be proved. Emphasis is given to the comparison with numerical and experimental results [1, 2] of nonequilibrium water vapour condensation in moist air over the **identical models** and at uniform free stream Mach numbers.

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Evaporation Wave Model for Superheated Liquids

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Abstract

Experiments with rapid decompression of superheated liquids (Chavez et al. 1985) and droplets exploding near the superheat limit (Shepherd and Sturtevant, 1982) reveal the existence of steady evaporation waves. An idealized model for steady evaporation waves has been analyzed. A evaporation wave is treated as a jump or discontinuity between metastable liquid and an equilibrium vapor or liquid–vapor mixture.

Numerical solutions of the jump conditions (Rankine-Hugoniot equations) have been obtained using Starling's equation of state to represent the thermodynamics of equilibrium and metastable states of hydrocarbon fluids. For simple fluids (small specific heat), only solutions with two-phase downstream states exist. Single-phase downstream states (complete evaporation waves) are predicted for complex fluids with a specific heat comparable to or greater than octane, given a sufficiently superheated initial state. Possible wave velocities range between zero and a maximum value determined by a Chapman-Jouguet condition.

This wave model is combined with a simple similarity description of liquid and vapor motion to predict the rates of steady spherical bubble growth in superheated liquids. The Chapman-Jouguet hypothesis is used to fix the evaporation rate and the results are compared with observations in bubble column experiments.

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EXPLOSIVE BOILING. SOME EXPERIMENTAL SITUATIONS

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Boiling assumes an explosive character when the power of heat release increases sharply or a volume of hot liquid is rapidly depressurized. The structure of a two-phase flow depends on the development of instabilities of different nature in it. It is difficult to choose an appropriate model and ensure a satisfactory accuracy of calculations for different space-and-time scales of flow of an extensively boiling liquid. In such a situation the study of separate fragments of a complicated problem making use of private models is of great importance. High-gradient flows are usually nonequilibrium because of the local incompleteness of the phase transition. It is connected with the insufficient density of the number of heterogeneous boiling centres.

The limit thermodynamic nonequilibrium corresponds to the attainment of liquid superheats at which intensive spontaneous boiling is observed on nucleus bubbles of fluctuation nature. The physical definiteness of this boundary is conditioned by a very sharp dependence of the nucleation rate $J(T,p)$ on the Gibbs number $G = W_*/k_B T$, where W_* is the work of formation of a critical nucleus [1, 2]. By the homogeneous nucleation theory the value of J is calculated making use of thermodynamic parameters. Thus, for water at atmospheric pressure (T_s = 373 K) and T = 573 K we have $J \simeq 10^{-3}\ s^{-1}m^{-3}$, and at T = 583 K the value of J increases by 23 decimal orders. It is important that the homogeneous nucleation theory is in good agreement with the experimental data [2, 3] obtained on small samples at high superheats.

The intensity of a flow of fluctuation vapour nuclei increases practically from zero to a very large value in a narrow temperature and pressure range. On a T, p constitutional diagram we have a belt that contracts at the thermodynamic critical point. This allows us to introduce the notion of shock or explosive boiling as a limiting regime under a rapid change of the liquid state with a deep penetration into the metastable region [2-4]. It is supposed that the action of ready and heterogeneous vaporization centres gives a relatively weak and "slurred over" contribution to the boiling process. The higher is the concentration of such centres in the system, the higher must be the rate of the state change to ensure explosive boiling. The term "limiting regime" is used in the sense that the evaluation of the number of arising vapour bubbles may be made by the homogeneous nucleation theory.

At our Institute various manifestations of the explosive (shock) boiling of liquids in high-gradient flows have been studied for many years. The space-and-time concentration of intensive homogeneous nucleation results in a strong hydrodynamic response of the system. The observed sign of this response (the liquid discharge through a short duct, the form of a free jet, the reactive force, the speed of motion of the boundary of a two--phase cloud) depends on the organization of the experiment. Every realized situation [5-9] is characterized by correspondence between some obvious peculiarity of the process and the conditions of realization of explosive boiling. If in an adiabatic process T_o, p_o are the initial parameters, $p_1 > 0$ is the terminal pressure, for T_o we have the condition $T_o \gtrsim 0.9\, T_c$, where T_c is the temperature of the thermodynamic critical point. We also have $p_o > p_s(T_o)$, p_s is the pressure on the saturation line.

The experiments were mainly carried out with n-pentane.

The model of explosive boiling allows us not only to give a qualitative explanation to the effects observed in two-phase nonequilibrium processes, but also to make trustworthy evaluations (for instance, of critical discharges through short ducts) that cannot be obtained making use of traditional schemes of the mechanics of heterogeneous media. The field of applicability of the model is outlined definitely enough. This model is a useful addition to other models of fluid mechanics.

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ABSTRACT

Korteweg Theory and van der Waals Fluids

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In this lecture I will survey the theory of liquid-vapor interfacial waves based on Korteweg's theory of capillarity. The main issue is the search for traveling wave and similarity solutions to the balance laws of mass, momentum, and energy when the effects of interfacial capillarity, viscosity, and heat conduction are included.

ON THE SIMILARITY CHARACTER OF AN UNSTEADY RAREFACTION WAVE IN A GAS–VAPOUR MIXTURE WITH CONDENSATION

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The unsteady expansion of a gas–vapour mixture caused by the instantaneous opening of a membrane in a Ludwieg tube is usually characterized by strong non–equilibrium processes with a relaxation time τ. When $t/\tau \to \infty$ the solution tends to a similarity solution. This similarity solution is investigated. It is shown that if condensation begins at a saturation ratio of unity, the expansion wave is divided into two zones, separated by a uniform region. This is due to the discontinuous character of the equilibrium speed of sound at the onset of condensation. If condensation occurs at a fixed critical saturation ratio $S_c > 1$, a condensation discontinuity is part of the solution. It is shown that a similarity solution is only possible if the condensation discontinuity is of the expansion type, which corresponds to the Chapman–Jouquet deflagration wave in an exothermically reacting medium. In this respect the unsteady rarefaction wave differs from the expansion in the diverging part of a Laval nozzle, where only compression type condensation discontinuities can exist.

An experimental set–up is described consisting of a tube of 12 m length and 0.1 x 0.1 m^2 cross–section, initially separated from a large vacuum vessel. Water vapour is thoroughly mixed with nitrogen gas and condensation nuclei. Pressure and density are measured during expansion. A three wavelength light extinction method is used to record droplet number density, modal droplet size, and the width of the droplet size distribution function. Experimental results are presented and compared with equilibrium theory.

STRONG EVAPORATION FROM A PLANE CONDENSED PHASE

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Abstract

The behavior of a semi-infinite expanse of a gas bounded by its plane condensed phase, where evaporation is taking place, is investigated numerically on the basis of the kinetic theory:

a) The time-development of disturbances starting from various initial conditions where the gas is in a uniform state of nonequilibrium condition with the condensed phase is studied in detail. The types of approach to the final steady states are clarified, and the decay of discontinuity in the velocity distribution function of the gas molecules due to molecular collision is investigated.

b) From the long-time behavior of the preceding analysis (or its simplified version), the possible steady evaporation from the plane condensed phase are derived: The relations among the variables at infinity and on the condensed phase and the behavior of the gas in the transition region (Knudsen layer) from the condensed phase to infinity, where the gas is uniform, are obtained. The relations obtained serves as the boundary condition for the macroscopic gas dynamic equations on the interface of a gas and its condensed phase.

c) The effects of various kinetic boundary conditions on the steady evaporation are studied. The results for the case where the diffuse reflection effect is incorporated in the convential boundary condition are found to be derived from those for the conventional condition by simple formulae.

EQUATIONS FOR ONE-DIMENSIONAL UNSTEADY FLOW OF BUBBLY LIQUIDS

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ABSTRACT

Unsteady flow of the mixture of liquid and gas or vapour bubbles is a complex physical process controlled by many factors: compressibility of both components, inertia and viscosity of the liquid, surface tension and others. A lot of attension has been paid to the problem of how to formulate equations of that flow. Van Wijngaarden has proposed a system of nonlinear equations for one-dimensional two-phase flow, taking into account the compressibility of the gas and the liquid as well as the liquid inertia. The continuity and momentum equations in his approach have been formulated for assumed uniform medium which has the substitutive density determined by the densities of both components and volumetric gas fraction coefficient β.

However, in the momentum equation the influence of the gas bubbles on the pressure force has not been considered. As the consequence, the characteristics ($\frac{dx}{dt} = u \pm a_l / \sqrt{1-\beta}$ - Rein) of govering equations show somewhat unphysical effect while the small disturbances can't propagate in the mixture faster than in the liquid alone (a_l).

In this paper equations for one-dimensional nonsteady flow of bubbly liquid for both gas and vapour bubbles are derived. Two models of wave propagation are considered. In the first one the inertia during the spherical motion of the liquid is taking into account whereas in the other it is neglected. In both models the nonuniform pressure distribution in the mixture is included. Physicaly, the correct result for velocity of waves propagation has been obtained.

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INTERACTION OF UNDERWATER SHOCK WAVES WITH AIR BUBBLES

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ABSTRACT

A result of holographic interferometric observation was presented concerning the interaction of underwater shock waves with air bubbles. In order to understand the shock-bubble interaction, 1.7 mm diameter air bubbles were exposed to underwater spherical shock waves. The spherical uderwater shock waves were generated by detonating a 10 mg silverazide pellet. Evaluating the fringe distributions of the holographic interferograms, it is revealed quantitatively that when the bubble was exposed to the underwater shock wave of overpressure 250 bar, a maximum pressure occurs on the side of the air bubble where the shock wave is loaded and the volume of the bubble becomes a minimum. The maximum pressure, at the next moment just like a point explosion in water, generates a rebound shock wave. A two-dimensional model experiment was also conducted where a cylindrical air bubble of 1.7 mm diameter was exposed to an underwater cylindrical shock wave. Since this is two-dimensional, simply by counting the fringe distribution the isobar was determined. It is found that the two-dimensional behavior of the bubble can simulate very well the three-dimensional case.

A numerical simuation was also conducted to the case where a air bubble of 1 mm diameter was exposed to an underwater planar shock wave having overpressure of 1 Kbar. Although in the computaion the physics was over-simplified, the result of the numerical simulation agrees qualitatively with the holographic interferometric observations.

STABILITY OF SHOCK WAVES AND GENERAL EQUATIONS OF STATE

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We consider the problem of stability of some shock wave configurations in fluids with general equations of state. On the background of studying the perturbation problem for the flow behind a shock in the tube we obtain the stability and instability conditions and classify the general equations of state on the basis of these conditions. It is shown that Bethe and Weyl thermodynamical conditions do not provide the stability of shock waves. Equations of state applied to describing phase transitions are also considered. The problem of stability of flows behind reflected oblique "weak" or "strong" shocks is studied for fluids with general equations of state, and conditions of correctness or incorrectness of the perturbation problem are obtained.

FIRST RESULTS FOR UNSTEADY FLOW WITH END STATES NEAR THE LIQUID-VAPOR CRITICAL POINT

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ABSTRACT

Shock-compression and wave-expansion experiments with near-critical end states are performed in a new shock tube with a specialized observation chamber. The tube can be operated as a shock or expansion tube. The experiments correspond to a reversal of those of Kutateladze et al., i.e., the flow state evolves toward the critical point, rather than away from it. Both retrograde and regular test fluids are used, including perfluoro-n-Hexane (shock compression, or wave expansion from a supercritical state), 2,2,4-Trimethylpentane (shock compression), sulfur hexafluoride (wave expansion) and perfluoro-n-Propane (wave expansion) are used, among others. Shock-reflection and rarefaction-wave reflection will occur at the endwall sapphire window of the observation chamber. Predictive calculations have been performed using the Hobbs and modified van der Waals equations.

Soundspeed, pressure and temperature are measured and the fluid is observed photographically. One objective of these experiments is to test for non-equilibrium behavior at short time scales. It is anticipated that experimental results will be available at the Symposium.

An additional steady-flow, near-critical experiment MACGONE is in the design stage. Research supported by the National Science Foundation.

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PHASE CHANGES OF A LARGE-HEAT-CAPACITY FLUID IN TRANSCRITICAL EXPANSION FLOWS

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ABSTRACT

Substances of large heat capacity are able to undergo complete adiabatic liquid-vapour phase changes. The soundspeed discontinuities at the phase boundaries give rise to various real flow effects. The investigation of Laval nozzle flows assuming phase equilibrium shows discontinues choking at the liquid phase boundary. At the vapour phase boundary up to three shocks can occur simultaneously in the nozzle: one expansion shock and two compression shocks.

In the experiment the initial conditions in the reservoir are chosen such that the expansion adiabats intersect the two-phase region close to the critical point. The phase boundary reached first during the expansion appears as a pronounced nucleation front. At the second phase boundary the influence of the distribution of liquid and vapour on the transfer processes becomes apparent. During the expansion process on subcritical adiabats the remaining liquid forms relatively large droplets. The transition to the pure gas flow spreads over a large spatial region. On supercritical adiabats, however, the two-phase state is reached coming from the gas phase. The re-evaporation of the small condensation nuclei is completed in a distinct evaporation front.

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